

One possible mechanism for massive neutron star supported by soft EOS

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The recently discovery of a massive neutron star (PSR J1614-2230 of $1.97 \pm 0.04 M_{\odot}$) rules out the soft equation of states (EOSs) such as those included hyperons or kaon condensates at high densities, while the nuclear theory or the terrestrial laboratory data prefer a soft EOS. Here we propose one possible mechanism to allow that the observed massive neutron star can be supported by a soft EOS, that is, if the the gravitational constant G varies at super strong field, a soft EOS can support the massive neutron stars.

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I. INTRODUCTION

As early as in 1937, Dirac pointed out that the gravitational “constant” G should not be a universal constant and it will decrease with the time [1]. After that, there are numerous literatures are involved in the alterable gravitational constant, see [2–7] etc. and references therein. Most of them focused on the time dependence of the gravitational constant, constrained by the different system, it is concluded that the time dependence of the gravitational constant is around $\dot{G}/G < 10^{-11} \text{ yr}^{-1}$ [2]. While also some authors argue that the gravitational constant should be replaced by a scalar field which can vary both in space and time, say, the gravitational constant in the Jordan-Fierz-Brans-Dicke theory [2, 8]. One recent work shows that by analyzing with a specifically selected equation of state (EOS), the discovery of a two-solar mass neutron star provided a constraint on the Newtonian gravitational constant, that is, it cannot exceed its value on Earth by more than 0.08 in the neutron star [9].

Through a roughly qualitative estimation, the acceleration of gravity g on the surface of the neutron star is about 10^{12} m/s^2 , which is far larger than that of the earth, $\sim 9.8 \text{ m/s}^2$. In such a totally different gravity circumstance, the possibility of a variational gravitational “constant” could be existent. On the other hand, the recently discovery of a massive neutron star (PSR J1614-2230 with $1.97 \pm 0.04 M_{\odot}$) rules out the soft EOSs [10], while both the nuclear theory and the terrestrial laboratory data prefer softer EOSs [11–14], where hyperons or kaon condensates may appear at high densities.

Stimulated by the very recent work [9] in which a constraint on the gravitational constant at strong field was put forward through the observation of massive neutron star, here we propose one possible mechanism to allow the observed massive neutron star to be supported by the soft EOS, say, an EOS for the neutron star matters including hyperons described by the relativistic $\sigma - \omega - \rho$ model (see the details in Section II). It is worth noting that the EOSs of the dense matters are still significantly model dependent up to date, for example, recent works show that even if hyperons exist in the stellar core, it is still allowed the neutron star has a maximum stellar mass larger than about $2.0 M_{\odot}$ [15, 16]. In fact, on the one hand, scientists manage to let the EOS of the dense matter become stiffer to resolve the puzzle that a soft EOS can not support the observed massive neutron stars [15, 16]. On the onther hand, there are also lots of efforts try to find a reasonable mechanism to let a soft EOS of the dense matter support the observed massive neutron star. One of the successful methods is considering the non-Newtonian gravity in the soft EOSs, which is equivalent to add a repulsive interaction in the dense matters and thus to let the EOS become stiffer [17, 18].

II. THE EQUATION OF STATE DESCRIBED BY RELATIVISTIC $\sigma - \omega - \rho$ MODEL

It is widely believed that at a density up to a few times the nuclear saturation density, the exotic hadronic matter such as hyperons or kaon condensates will appear, which makes the EOS of the neutron star matters become significant softer than those only include neutrons, protons and electrons (npe)[13, 14, 19, 20]. As an example, here we employ one soft EOS investigated by the relativistic $\sigma - \omega - \rho$ model, where hyperons are included at high densities. This model is described by a Lagrangian density as [21–26]

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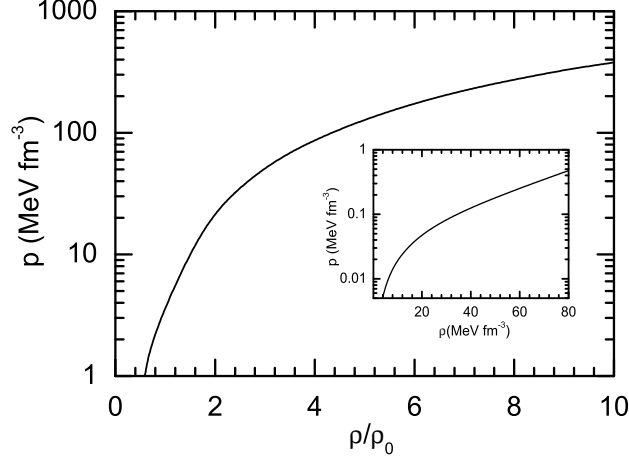


FIG. 1: The equation of state of the neutron star matters including hyperons, where the energy density ρ is in units of the saturation density ρ_0 , and the insert shows the EOS of the crust.

$$\begin{aligned}
L = & \sum_B \bar{\psi}_B (i\gamma_\mu \partial^\mu + m_B - g_{\sigma B} \sigma - g_{\omega B} \gamma_\mu \omega^\mu - \frac{1}{2} g_{\rho B} \gamma_\mu \vec{\tau} \cdot \vec{\rho}^\mu) \psi_B + \frac{1}{2} (\partial\sigma)^2 \\
& - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - U(\sigma) - \frac{1}{4} \vec{\rho}_{\mu\nu} \cdot \vec{\rho}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu \\
& + \sum_l \bar{\psi}_l (i\gamma_\mu \partial^\mu - m_l) \psi_l
\end{aligned} \tag{1}$$

where

$$U(\sigma) = a\sigma + \frac{1}{3!} c\sigma^3 + \frac{1}{4!} d\sigma^4, \tag{2}$$

$$F_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \tag{3}$$

$$\vec{\rho}_{\mu\nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu, \tag{4}$$

ψ_B is the field operator of baryon B ($B=n, p, \Lambda, \Sigma, \Xi, \Delta$); ψ_l is the field operator of lepton l ($l=e, \mu$); $\sigma, \omega^\mu, \vec{\rho}^\mu$ are the field operators of σ -, ω -, ρ - meson, respectively; $g_{\sigma B}, g_{\omega B}, g_{\rho B}$ are the coupling constants between σ -, ω -, ρ - meson and baryon, respectively; m_B, m_l, m_i ($i = \sigma, \omega, \rho$) are the mass of baryon, lepton, meson, respectively; and $\vec{\tau}$ is the isospin operator. From the Lagrangian density described by Eq. 1, the EOS of the neutron star matters can be obtained. In the numerical calculation, the following parameters are adopted [26]: $a = -2.1 \times 10^7 \text{ MeV}^3$, $c = 0.97 M_n$, $d = 1277$, $g_s = 6.73$, $g_v = 8.59$, $M_n = 938 \text{ MeV}$, $m_\omega = 783 \text{ MeV}$, $m_\sigma = 550 \text{ MeV}$, $m_\rho = 770 \text{ MeV}$ and $K = 224 \text{ MeV}$. Similar to other models, the parameters adopted here are obtained by fitting and reproducing the saturated properties and the symmetric energy of the nuclear matter. The EOS is displayed in Fig. 1. For the density below about 0.07 fm^{-3} , the results of Refs. [27, 28] are employed, which is shown in the inset of Fig. 1.

III. NUMERICAL RESULTS AND DISCUSSION

Before presenting the numerical results, we first briefly review the structure equation of the static neutron stars. Here we only consider the relativistic hydrostatic equilibrium cases. The equilibrium of a spherical perfect fluid star

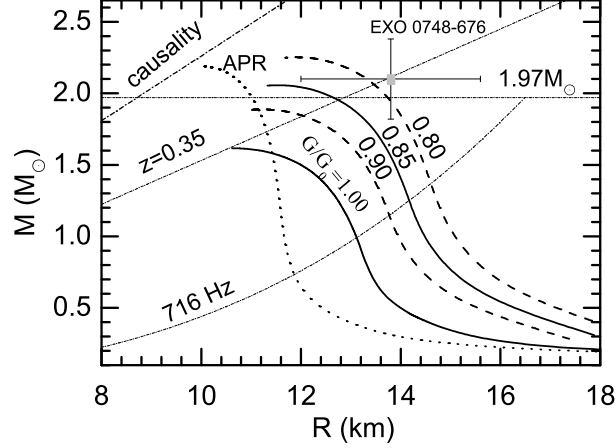


FIG. 2: The mass-radius relation of static neutron stars with different gravitational constant G . The value G/G_0 is indicated by the numbers beside the lines, where $G_0 = 6.6738 \times 10^{-11} (m^3 kg^{-1} s^{-2})$.

is described by a static, spherically symmetric space-time with metric of the form

$$ds^2 = -e^{2\nu} dt^2 + e^{2\lambda} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2), \quad (5)$$

where ν and λ are the functions of r only.

Supposing the matter of a static spherically symmetric neutron star can be treated as perfect fluid, therefore its energy-momentum tensor can be described by

$$T_{\mu\nu} = pg_{\mu\nu} + (p + \rho)u_\mu u_\nu, \quad (6)$$

then according to the Einstein field equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -8\pi GT_{\mu\nu}, \quad (7)$$

the Tolman-Oppenheimer-Volkoff (TOV) equations of the relativistic hydrostatic equilibrium can be obtained [29, 30]

$$\frac{dp}{dr} = -\frac{G}{c^2} \frac{(p + \rho)[m(r) + 4\pi r^3 p]}{r[r - 2Gm(r)/c^2]}. \quad (8)$$

Here the gravitational constant G in Eq. 8 is considered as a alterable “constant”. In the numerical calculation for the neutron star structure, the variational G is denoted by the ratio G/G_0 , where $G_0 (= 6.6738 \times 10^{-11} m^3 \cdot kg^{-1} \cdot s^{-2})$ is the Newtonian gravitational constant on earth.

Shown in Fig.2 is the mass-radius relation of static neutron stars with varying gravitational constant obtained from solving the TOV equations. it is shown that if we do not consider the variation of the gravitational constant ($G/G_0 = 1$), the corresponding sequence neutron star can only support a maximum mass about $1.61M_\odot$, which is obviously can not support the observed mass $1.97 \pm 0.04M_\odot$ of PSR J1614-2230. In addition, as shown in Fig. 2, for this sequence of neutron star, it is hard to support a redshift $z = 0.35$ [31]. In order to support a stellar mass up to $1.97M_\odot$, one needs the gravitational constant decreasing down to about $G/G_0 = 0.87$. If we want the neutron star sequence can support the observation of EXO 0748-676 (with $M \geq 2.10 \pm 0.28M_\odot$ and $R \geq 13.8 \pm 1.8km$) [32], the gravitational constant should best decline to about $G/G_0 = 0.80$. For comparison, the mass-radius relation of the widely used APR EOS [33], which consists of neutrons, protons, electrons and muons, is also plotted in Fig.2, where the variation of the gravitational constant is not considered. One can see that though the neutron star sequence of APR EOS can support the mass observation of PSR J1614-2230, it can not support the observed radius of EXO 0748-676.

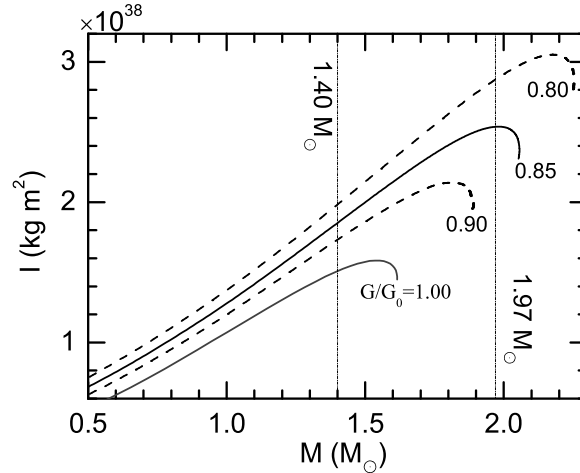


FIG. 3: The momenta of inertia of the slowly rotating hyperon stars with different gravitational constant (denoting by the numbers of G/G_0 below the endpoints of lines) as a function of the stellar masses.

As the moment of inertia can provide an important observational constraints for the neutron stars, and the discovery of the double-pulsar system PSR J0737-3039 *A&B* provides a great opportunity to determine accurately the moment of inertia I of the star *A* [34, 35], so it is also interesting to investigate the effect of the gravitational “constant” G on the moment of inertia. The moment of inertia is defined by

$$I = \frac{J}{\Omega} \quad (9)$$

where Ω is the star’s angular velocity, and J is the angular momentum. For the rotational frequency much lower than the Kepler frequency, approximating to the first order terms in Ω , the moment of inertia can be estimated by an available empirical equation [36]

$$I \approx 0.237 MR^2 \left[1 + 4.2 \frac{M}{M_\odot} \frac{km}{R} + 90 \left(\frac{M}{M_\odot} \frac{km}{R} \right)^4 \right]. \quad (10)$$

The momenta of inertia of the neutron star sequence with different gravitational constant are presented in Fig.3. It is shown that the effect of the gravitational constant on the momenta of inertia is obvious. For a canonical neutron star mass ($1.4M_\odot$), the increment of the momenta of inertia of a star with $G/G_0 = 0.80$ comparing with that of $G/G_0 = 1$ is about 33%. If the moment of inertia of neutron stars can be measured accurately like the mass measurement someday in the future, the momenta of inertia can provide a probe to investigate the variation of gravitational constant.

In summary, we have proposed an effective mechanism to allow the observed massive neutron star be supported by soft EOSs, that is, the decrease of gravitational “constant” G at super strong field brings about the mechanism that a soft EOS can support the astro-observation of massive neutron stars.

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